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Mundinger et al.

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[54] **WASTE HEAT REMOVAL SYSTEM**

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[73] Assignee: **SDL, Inc.**, San Jose, Calif.

[21] Appl. No.: **93,206**

[22] Filed: **Jul. 16, 1993**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 992,127, Dec. 16, 1992, abandoned.

[51] **Int. Cl.**^{6} **H01L 25/04**; H01L 23/02

[52] **U.S. Cl.** **257/714**; 257/712; 361/689; 361/699; 361/700; 165/104.21; 165/104.26; 165/104.33

[58] **Field of Search** 257/712, 713, 257/714, 715; 372/35; 165/104.26, 104.33; 361/700

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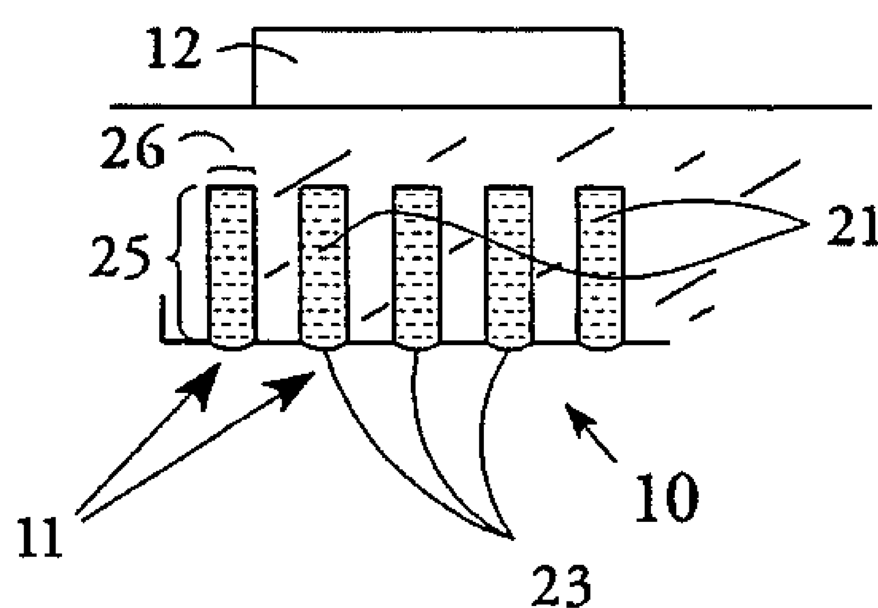
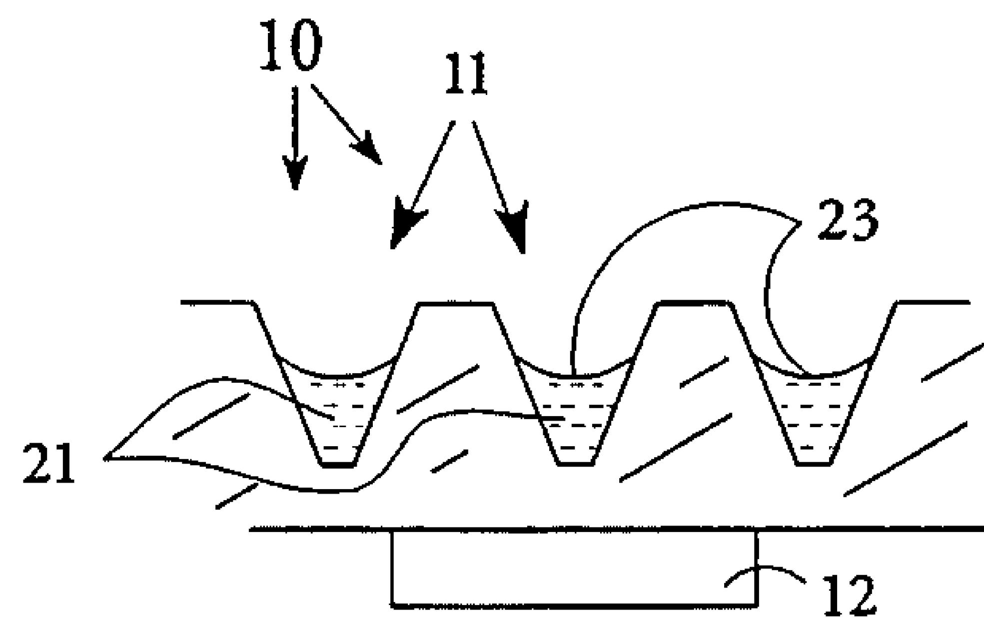
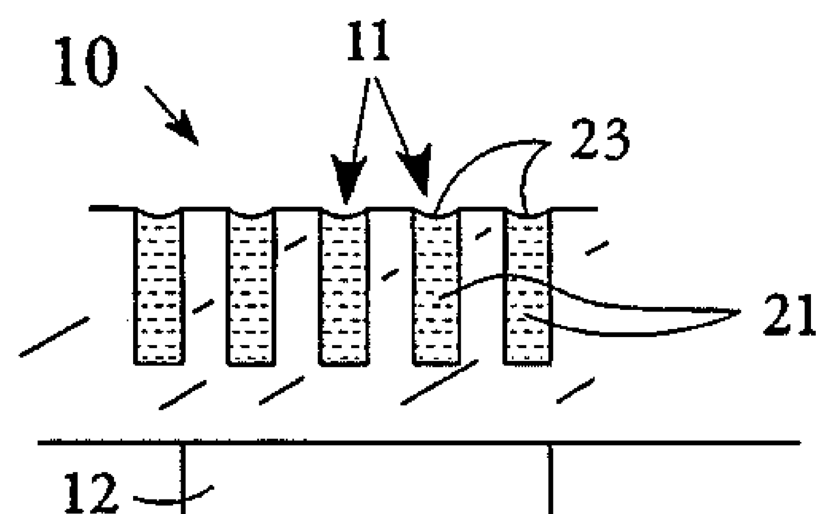
[57] **ABSTRACT**

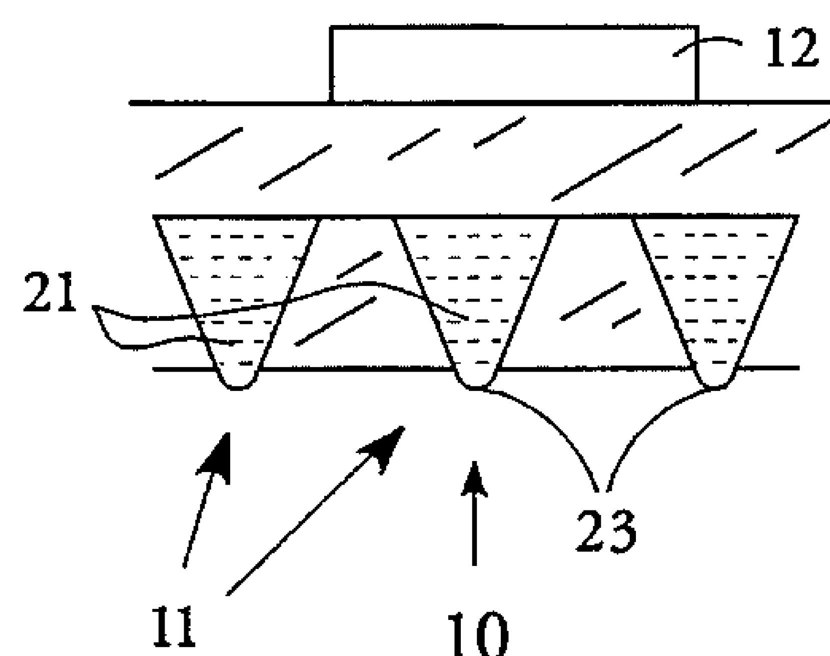
A cooling device formed in a thermally conductive substrate having at least one microchannel of dimensions that induce capillary action and a surface in thermal contact with a heated region. The microchannel has a longitudinal opening oriented away from the heated region and is supplied with liquid coolant which is contained by a meniscus near the opening. The coolant vaporizes at the meniscus and absorbs heat but, due to increased pressure in the coolant contained by the meniscus, does not boil within the microchannel, allowing more liquid coolant contact with the thermally conductive substrate and walls. The vaporized coolant is discharged into a chamber facing the opening which can be at a lower pressure to remove additional heat by gaseous expansion. The discharge of gaseous coolant allows the capillary flow of the liquid coolant in the microchannels to be unimpeded, and may be augmented by a fluid pump. The gaseous coolant may be in thermal contact with a condenser that liquefies the coolant for supply to the microchannels, by an array of capillaries, in a self contained cooling device. An array of such devices is provided with holes and stacked to connect adjacent liquid and gaseous coolant flows to cool an array of heated objects, such as laser diode bars.

34 Claims, 6 Drawing Sheets









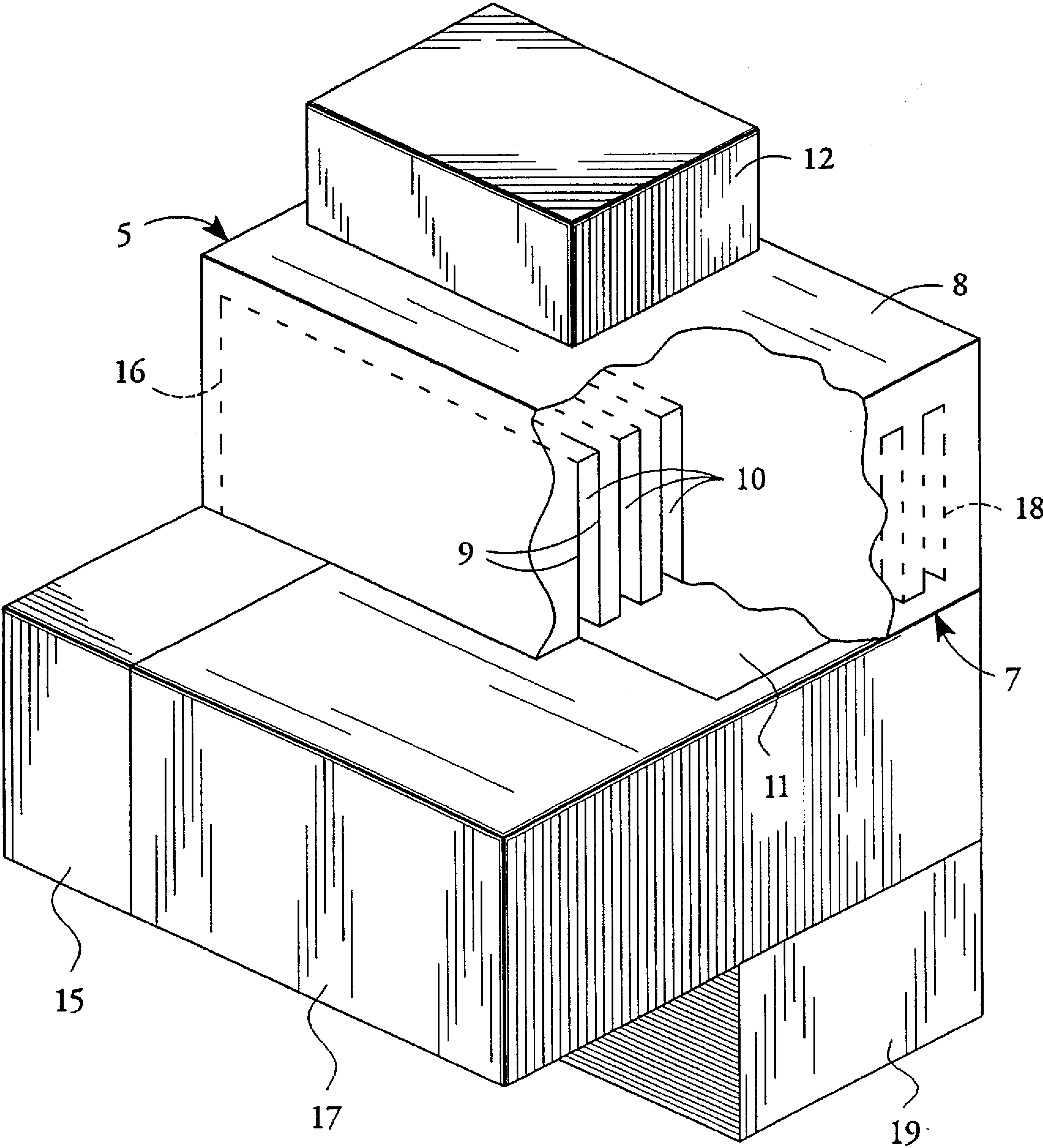


FIG. 1

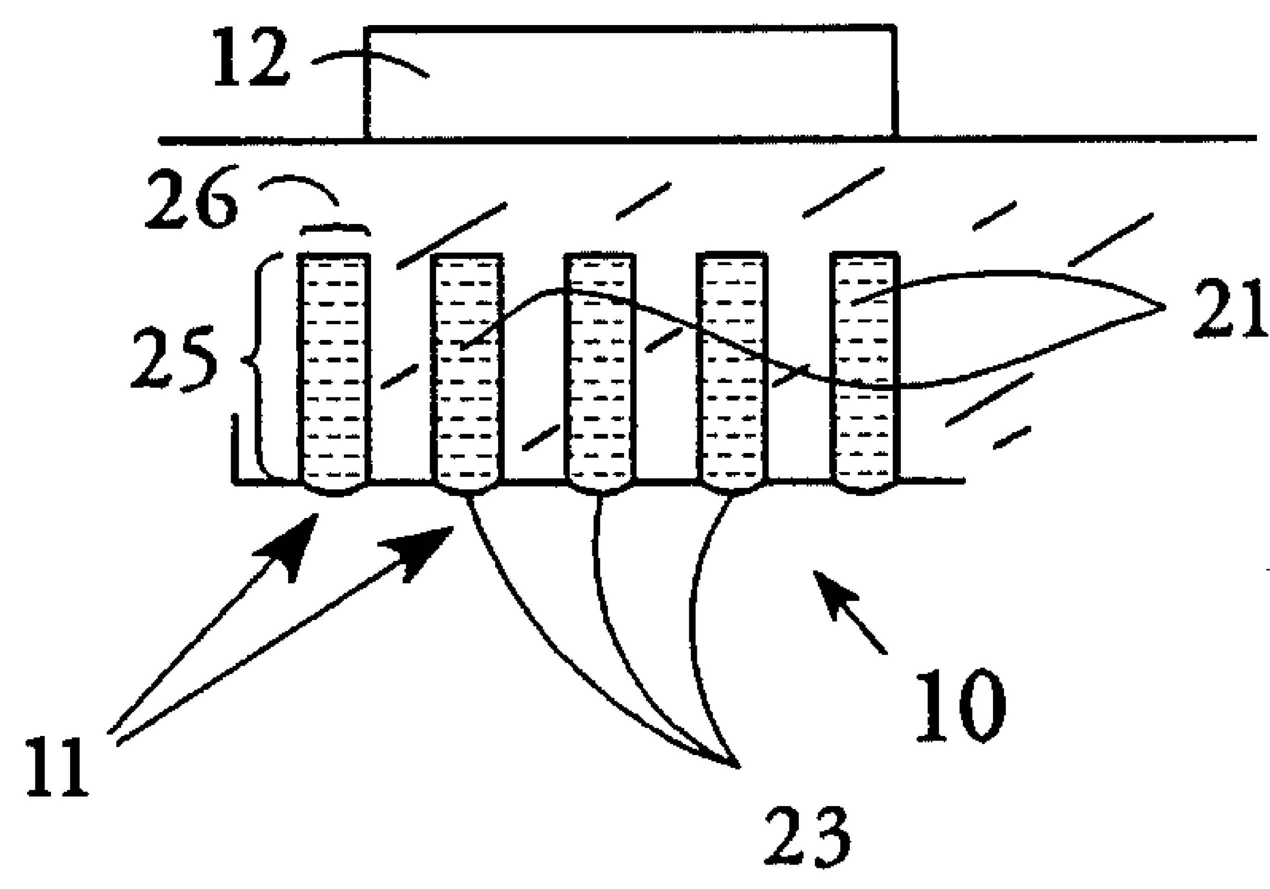


FIG. 2a

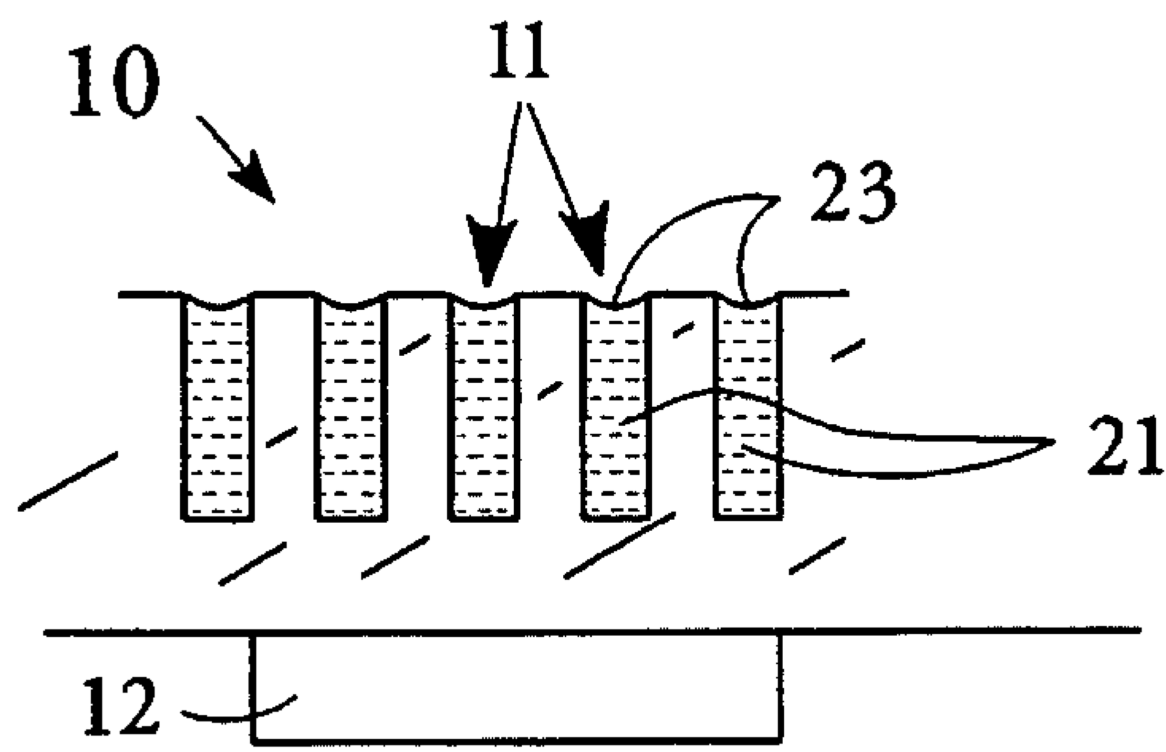


FIG. 2b

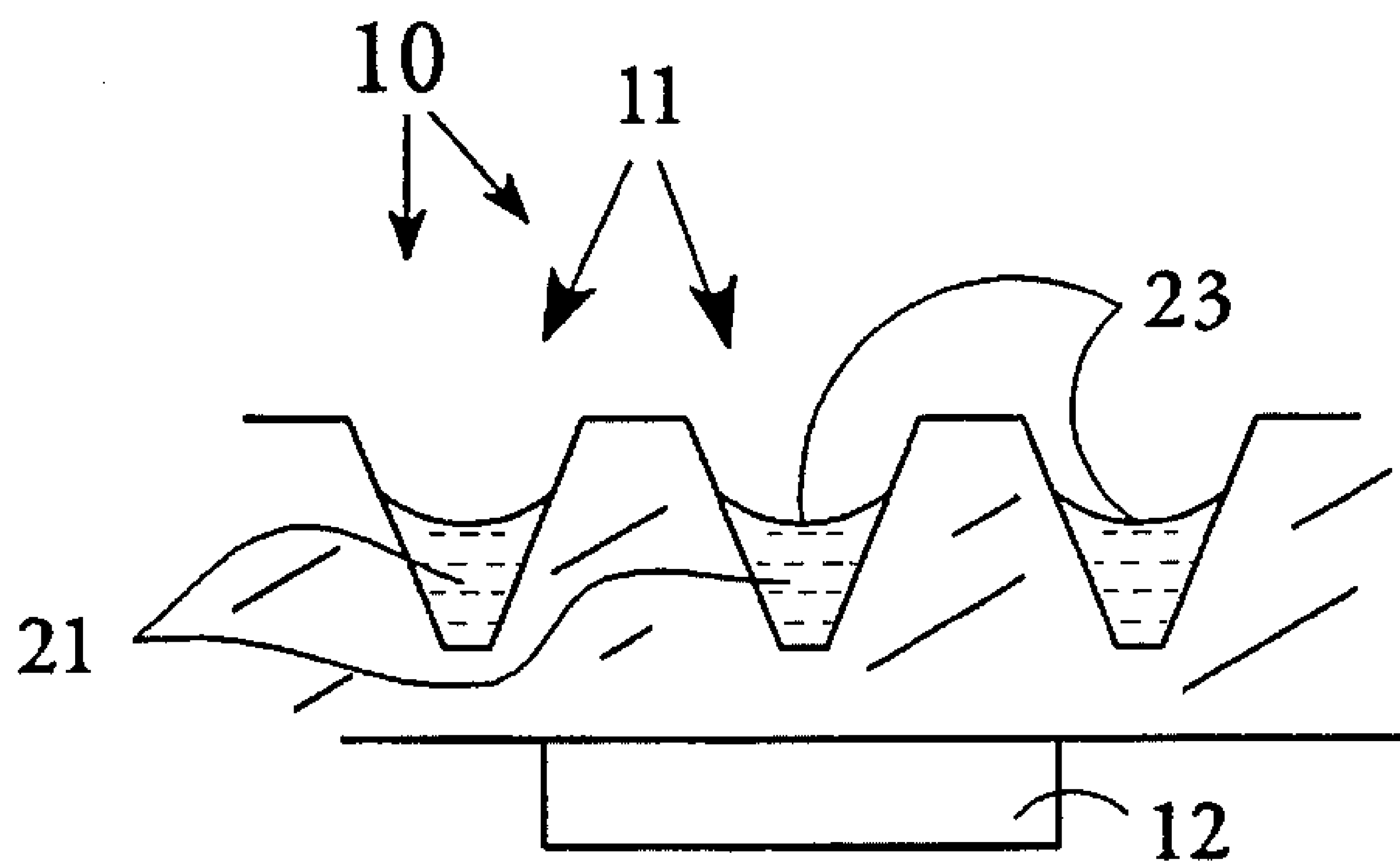


FIG. 2c

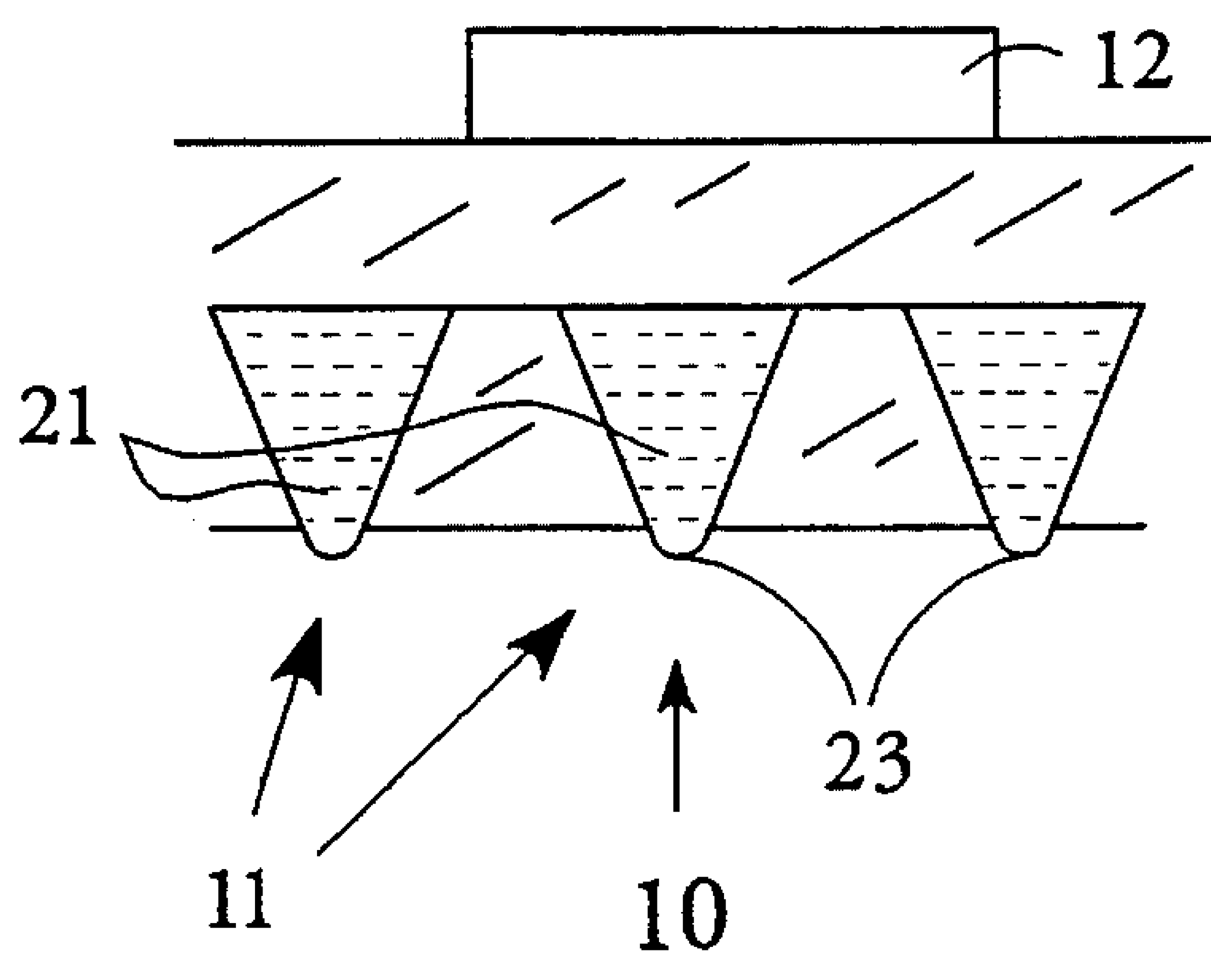


FIG. 2d

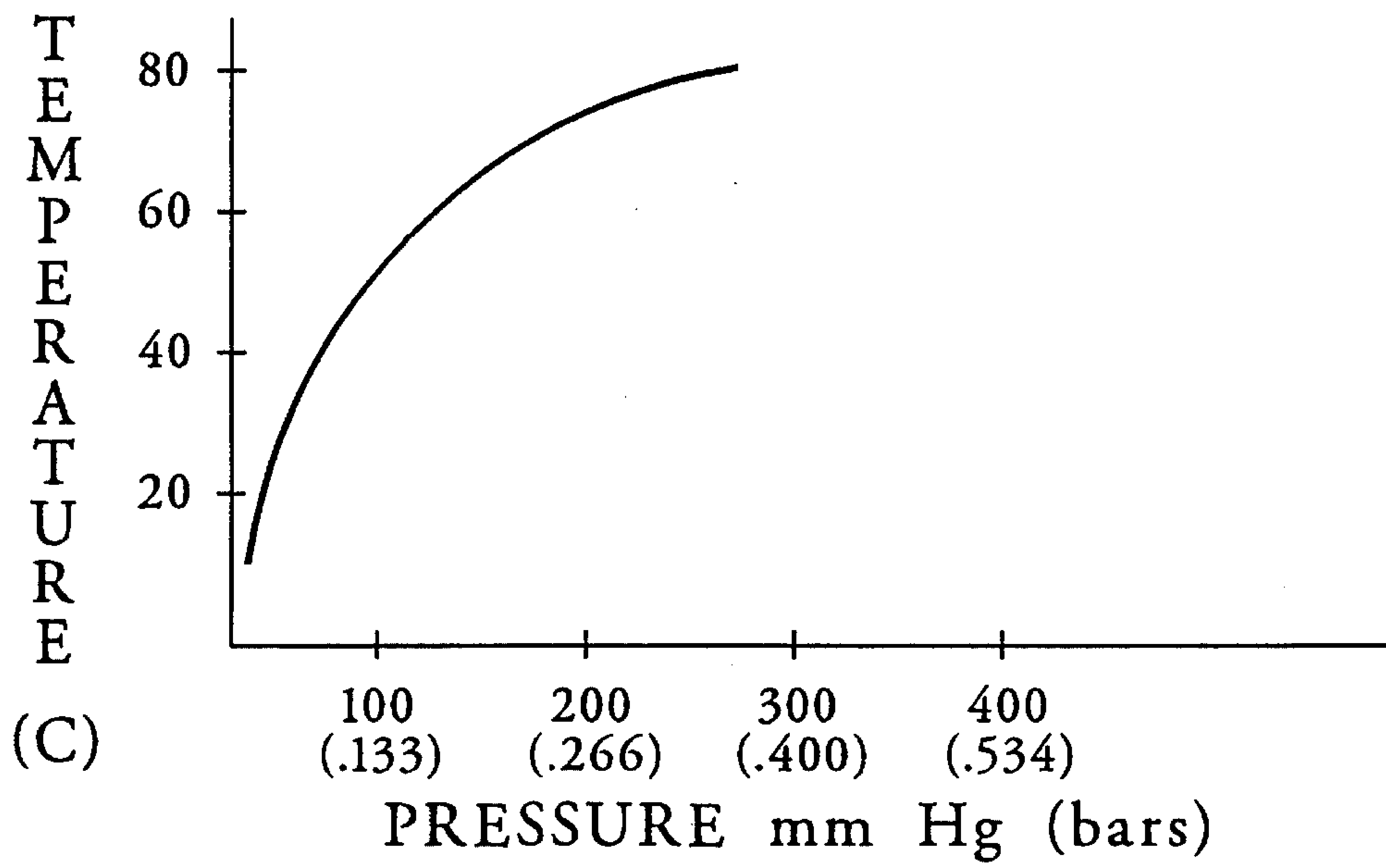


FIG. 3

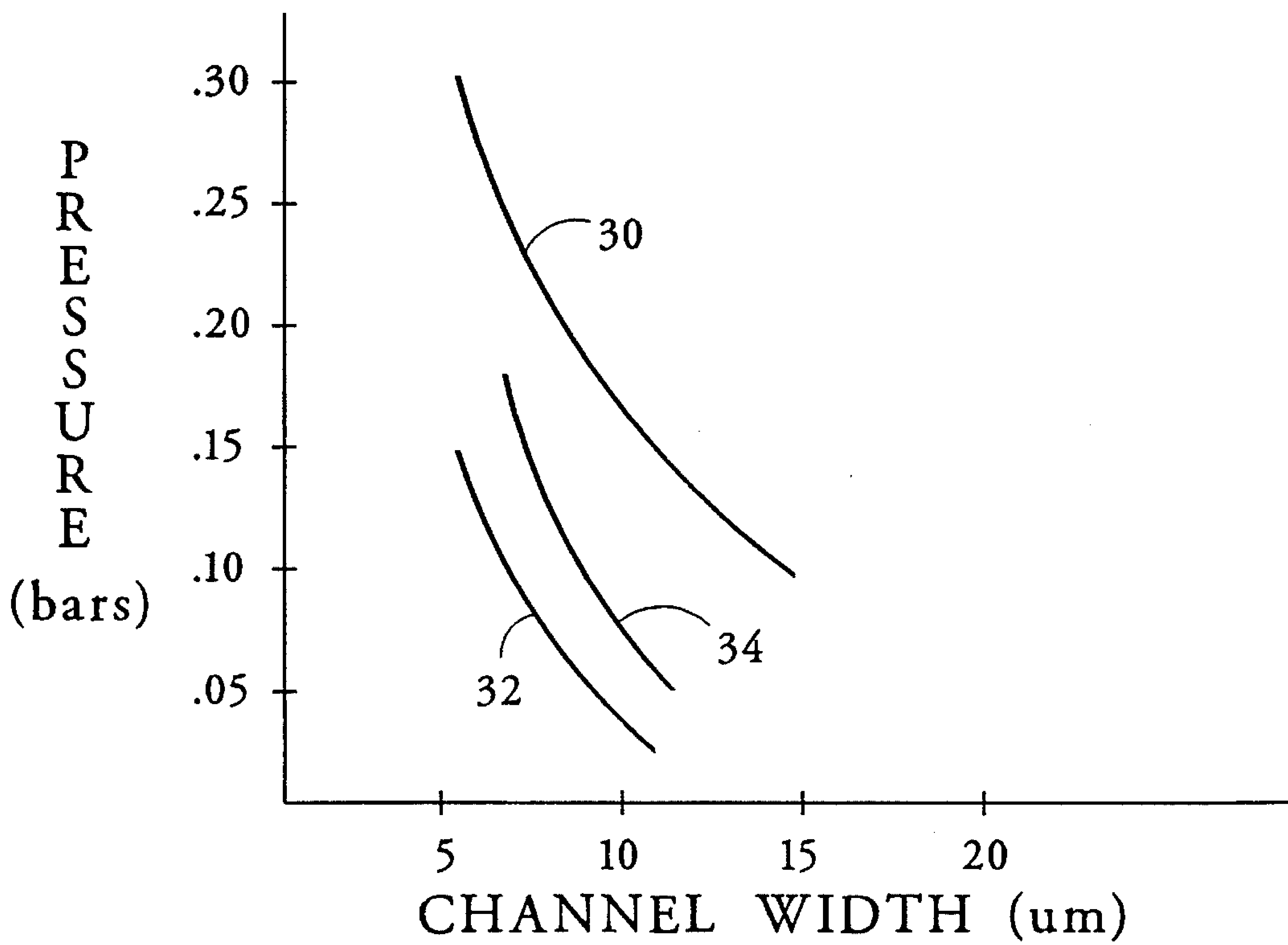


FIG. 4

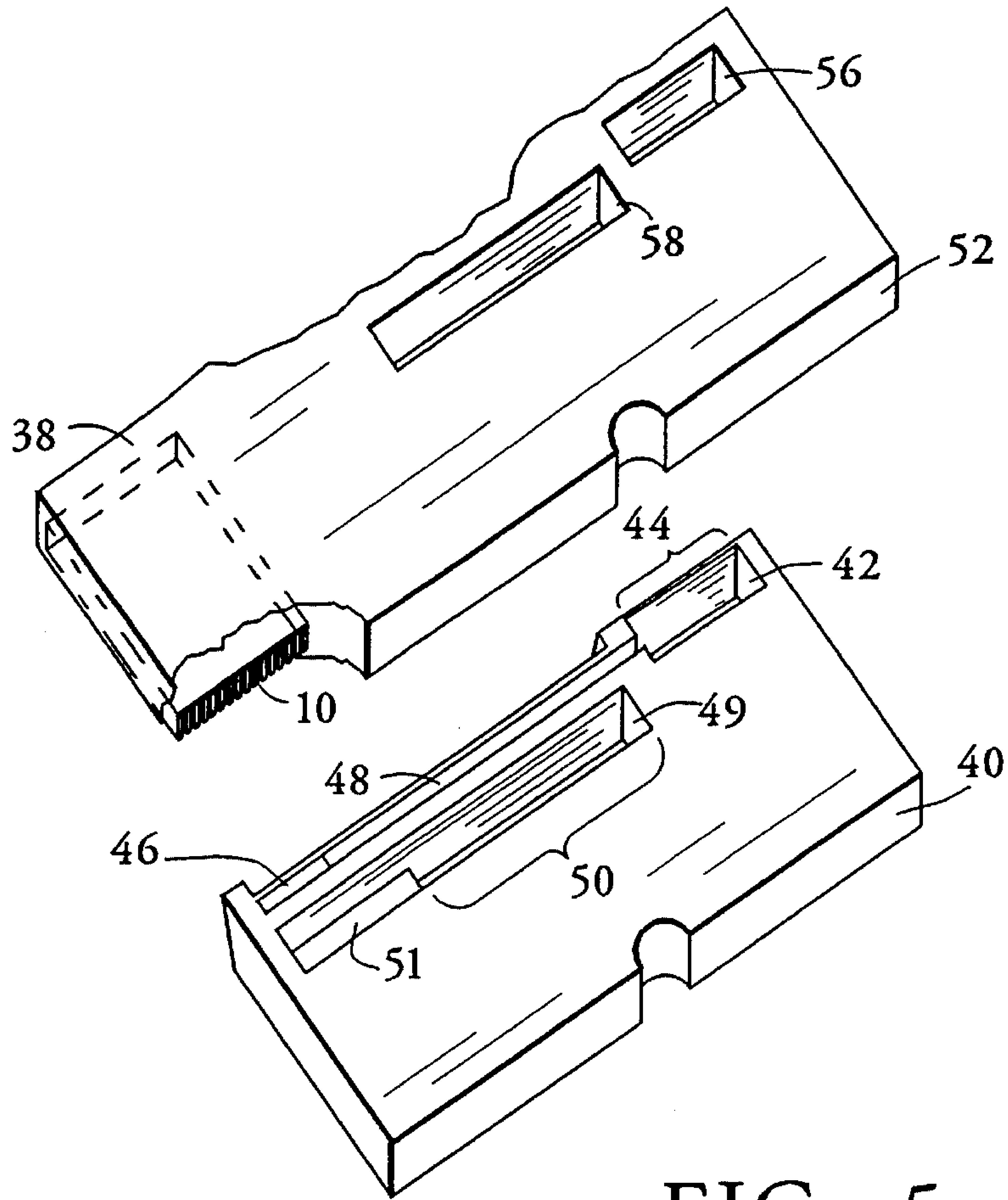


FIG. 5

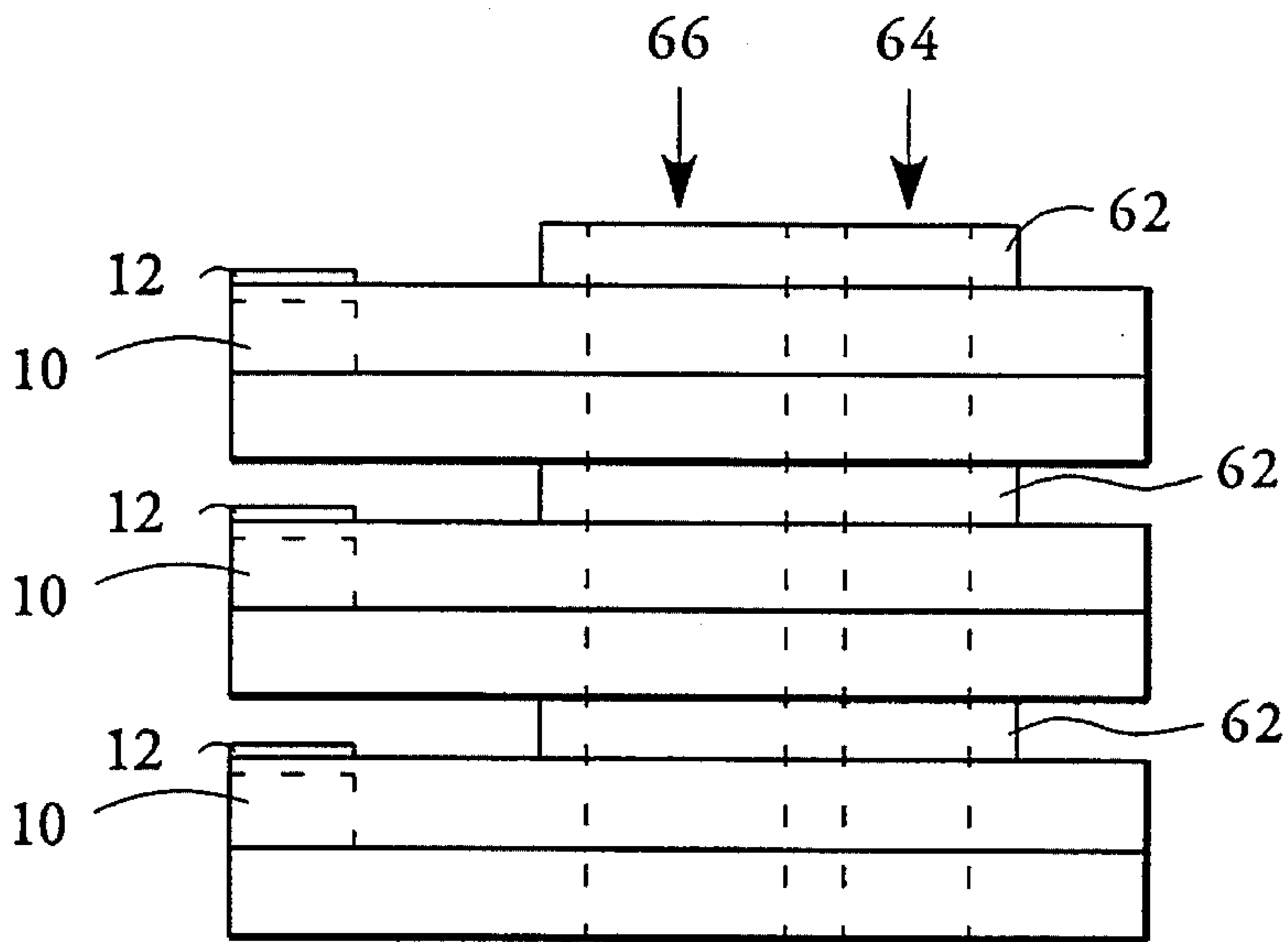


FIG. 6

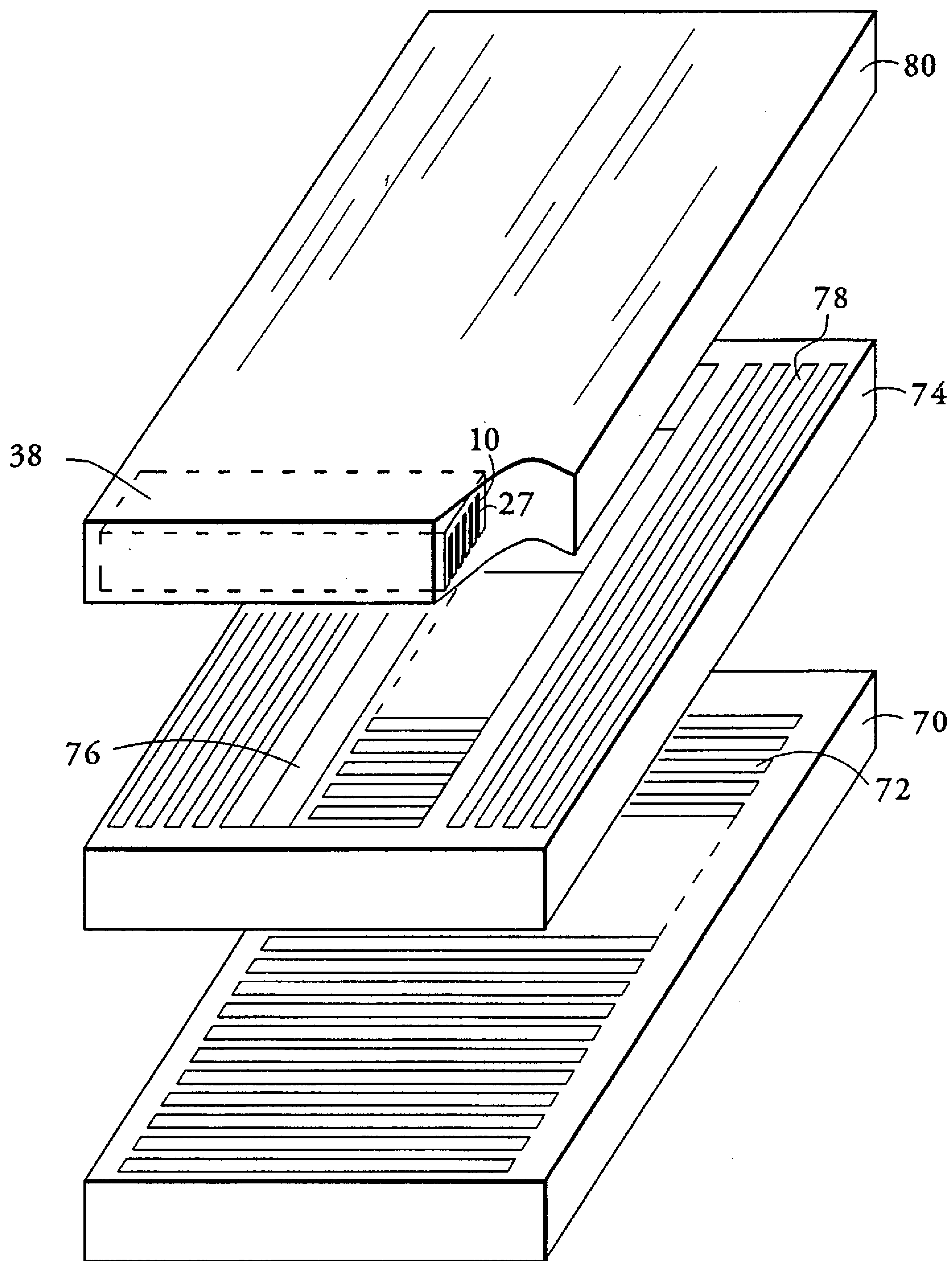


FIG. 7

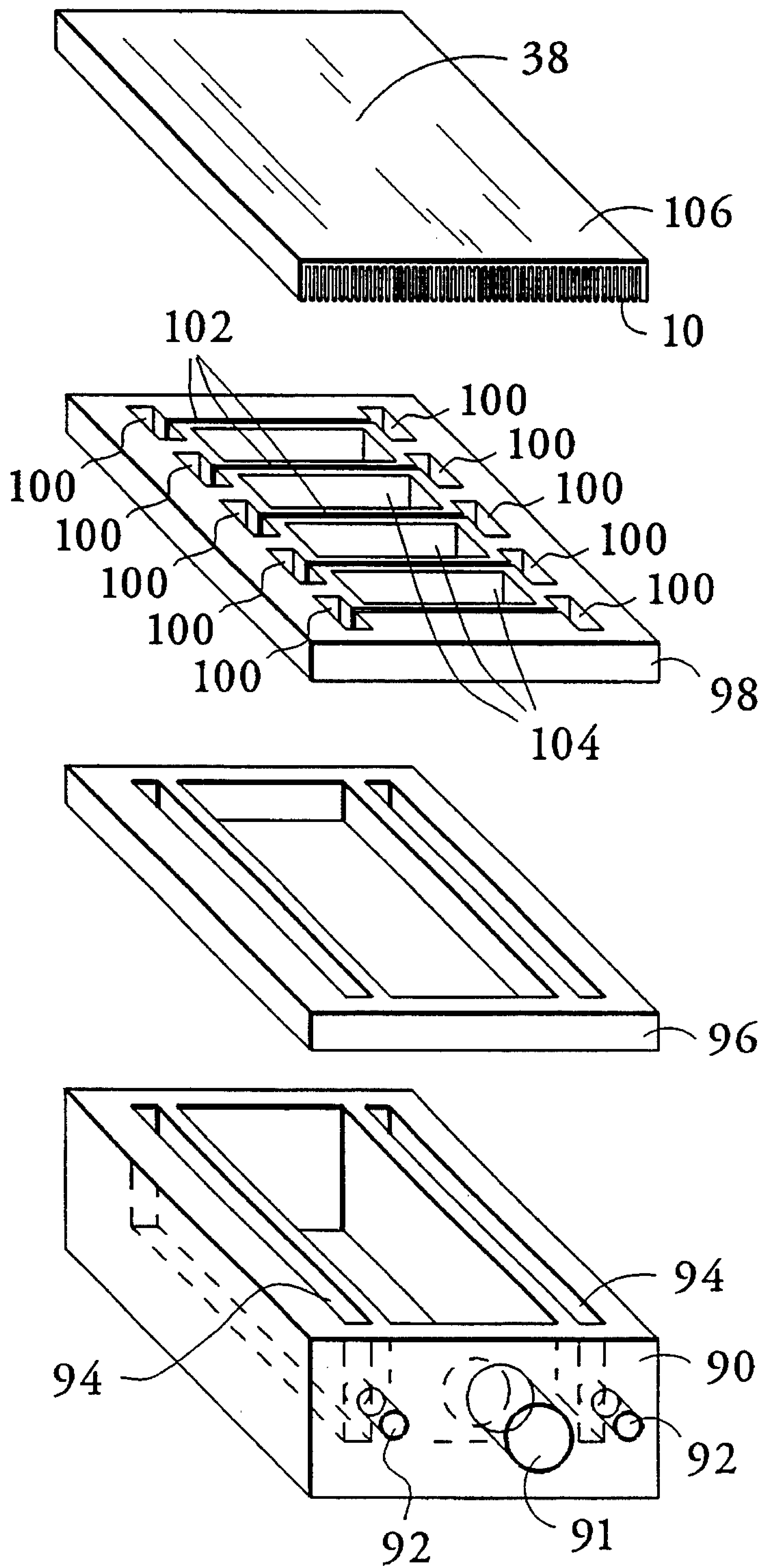


FIG. 8

WASTE HEAT REMOVAL SYSTEM

CROSS REFERENCE TO RELATED APPLICATION

This is a continuation-in-part of patent application Ser. No. 07/992,127 filed Dec. 16, 1992, now abandoned.

TECHNICAL FIELD

The present invention pertains to cooling of heated regions. More particularly, the present invention relates to cooling of microelectronic devices such as laser diodes and cooling of arrays of such devices.

BACKGROUND ART

Excess heat is generated in many electrical and mechanical applications. Microprocessors, for example, may generate excess heat through internal electrical resistances. Mechanical devices such as those employing micro-machined gears and components also generate unwanted heat through friction between contacting surfaces. Heat produced by such systems can severely hamper the performance and reliability of the devices. In an attempt to alleviate the problem of excess heat generation, such devices are often soldered onto a heat sink formed of a thermally conductive material such as copper. Although heat sinks are somewhat effective in removing small amounts of heat, as the amount of heat produced is increased, the finite conductivity and diffusivity of the material used as a heat sink becomes a limiting factor. Even for the most thermally conductive materials such as diamond, the rate of heat transfer away from the device is not fast enough to keep up with the rate at which heat is produced. As a result, unacceptable temperature rises occur thereby limiting the performance and reliability of the device.

Microchannel cooling systems have been introduced which use a liquid such as water for cooling a heat source. In such systems, tunnels or grooves are formed into the substrate supporting the heat generating device. A liquid coolant (typically water) is then pumped through the tunnels in an attempt to remove excess heat generated by the device. These systems are designed to get the liquid coolant very close to the heat source, to further facilitate heat removal. However, the tunnels require a high pressure to maintain sufficient flow of the liquid coolant. As the number of tunnels is increased, and the corresponding size of the tunnels is decreased, the frictional forces on the coolant become substantial and, eventually, prohibitive. Furthermore, the performance of the system is still limited by the finite heat capacity of the water and the ability to get the heated coolant or vapor away from the heat source and fresh coolant into the region.

Heat pipes are also a well known method for providing system cooling. Heat pipe systems utilize a porous material such as sintered metal, ceramic, screens, or webbing as a wick to supply liquid coolant to the area from which excess heat is to be removed. The wick draws the coolant into the desired region through capillary pressure. As the coolant in the wick passes near the heat generating device, excess heat is absorbed through warming or, more commonly, vaporization of the coolant. Unfortunately, wick-type cooling systems also suffer from severe drawbacks. As the coolant in the wick is vaporized, increased pressure is created within the wick. The resultant pressure impedes the flow of new coolant through the wick and into the area where it is most needed. Additionally, the vaporized coolant tends to dry out the wick as it moves through it. Often, as the wick dries out, the temperature of the device rises substantially.

Therefore it is an object of this invention to provide for the efficient dissipation of heat from a heated region having the advantages of conventional microchannel and wick-type systems, but which does not have restricted or impeded flow of liquid coolant, and which does not dry out as quickly due to the flow of vaporized coolant through the system.

SUMMARY OF THE INVENTION

This object has been achieved with a compact heat dissipation device utilizing an array of microchannels formed in a thermally conductive substrate at a location near the heated region. The microchannels are of a size that induces capillary action, are continually supplied with a liquid coolant, and are open in a direction away from the heated region, except for a meniscus which forms between opposite walls of the microchannel and helps confine liquid coolant therein. Due to the size and shape of the microchannels, a pressure gradient is formed in the liquid coolant disposed within the microchannels, such that the pressure near the heated region is substantially higher than the pressure further from the heated region, in the meniscus near the opening of the microchannels. In addition, the thermal conductivity of the substrate allows heat to travel through the walls separating the microchannels providing a fairly even heating of the liquid coolant disposed within the microchannels. Due to the combination of pressure gradient and the fairly even temperature distribution within the microchannels, the coolant is prevented from boiling at the high pressure region near the heated region, instead vaporizing only at the meniscus. The change of the coolant phase from a liquid to gaseous state absorbs a significant amount of heat from the heated region, transferring heat to the vapor, while preventing the liquid from boiling near the heated region allows the efficient conduction of heat and prevents the microchannels from drying out.

The opening of a microchannel discharges gaseous coolant into a voluminous chamber. Cooling of the device is augmented by expansion of the gaseous coolant as it flows into the chamber, encouraged by a lower pressure in the chamber than at the opening. The pressure may be reduced in the chamber by a gas pump or by convection caused by a condenser in thermal communication with the chamber. The condenser is maintained at a temperature which liquefies the gaseous coolant in the chamber.

Although any means for supplying liquid coolant to be drawn by capillary action into the microchannels and any separate means for discharging gaseous coolant from the openings of the microchannels can be used with this device, a particular improvement is disclosed which utilizes a second substrate which contains a plurality of passageways and which is bonded to the bottom of the first substrate such that a portion of the passageways are in fluid communication with the microchannel. Liquid coolant is then provided via one or more of the passageways to the microchannels, where it is disposed in close proximity to the heated region through capillary action induced by the microchannel. A preferred means of supplying liquid coolant involves a second array of microchannels feeding fluid to the microchannels that are proximate to the heated region. The coolant is vaporized from the meniscus in the microchannels proximate to the heated region, and the vapor is vented from the those microchannels through one or more different, larger pas-

sageways. In so doing, a continuous flow of coolant is provided to the microchannels and the vaporized coolant is removed through a different route so that the flow of coolant to the microchannel array is not impeded.

The heat dissipating devices can be used to cool devices such as laser diodes that are bonded to the thermally conductive substrate. Combinations of a laser diode, a thermally conductive substrate, and a second substrate can be stacked in arrays that are cooled using a single source of liquid coolant and a single repository for gaseous coolant.

As a result, the present invention provides for the dissipation of higher levels of waste heat than was previously possible. This in turn enables higher performance and increased reliability levels in the devices being cooled, such as laser diodes and laser diode arrays.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of a heat dissipation apparatus in accord with the present invention.

FIGS. **2***a*–**2***d* is a cross-sectional view of liquid coolant contained by surface tension in several microchannel embodiments.

FIG. **3** is a chart of boiling point vs. pressure of water.

FIG. **4** is a chart of water pressure caused by surface tensions vs. width of the microchannels.

FIG. **5** is an exploded perspective view of an alternate embodiment of a heat dissipation apparatus in accord with the present invention.

FIG. **6** is an elevated side view of the heat dissipation apparatus of FIG. **2** shown in a stacked and bonded array in accord with the present invention.

FIG. **7** is an exploded perspective view of another alternate embodiment of a heat dissipation apparatus in accord with the present invention.

FIG. **8** is an exploded perspective view of yet another alternate embodiment of a heat dissipation apparatus in accord with the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

With reference to FIG. **1**, a perspective view of a preferred embodiment of the heat dissipation apparatus of the present invention is shown. A thermally conductive substrate **5** is shown, with an array of microchannels **10** carved therein. The microchannels **10** have walls **9** spaced sufficiently close to each other to induce capillary action. The microchannels **10** are elongated and have openings **11** only at a bottom **7** of the substrate **5**, while a top **8** of the substrate is disposed proximate to a source of heat **12**. A fluid source **15** supplies liquid coolant (not shown) to one end **16** of the microchannels **10**, and capillary action draws the coolant into the microchannels. The exact form of the fluid source **15** is not essential to the invention. A chamber **17** for discharge of gaseous coolant (not shown) is in gaseous communication with the openings **11** of the microchannels **10**. The exact form of the chamber **17** is not essential to the invention.

Vaporization of the coolant, aided by heat from the source of heat **12**, occurs in the liquid coolant disposed within the microchannels **10** at a meniscus (not shown) proximate to the openings **11**, and the gaseous coolant is removed through the chamber **17**. Boiling of the coolant within the microchannels is restrained by the dimensions of the microchannels **10** which induce capillary action. Since boiling of the coolant is inefficient, as it produces gas bubbles which reduce the amount of liquid coolant in close proximity to the source of heat **12**, the lack of boiling within the microchannels **10** adds to the cooling ability of the invention.

A condenser **19** may be placed in thermal contact with the gaseous coolant in the chamber, the condenser **19** causing the gaseous coolant to liquefy, the liquefied coolant providing coolant to the fluid source **15**.

Another preferred embodiment of the invention (not shown) is identical to the embodiment described above, except that the fluid source **15** is in communication with the microchannels **10** at an end **18** of the microchannels opposite to the end **16**, and supplies liquid coolant to ends **16** and **18** simultaneously, while gaseous coolant is discharged from the openings **11** and removed by a chamber **17** located between the ends **16** and **18**.

The chamber **17** has a much larger volume than the microchannels **10** in order to accommodate the expansion in volume of the coolant as it changes from a liquid to a gaseous phase. When the gas pressure in the chamber **17** is less than that at the openings, as can be provided with a gas pump or with convection that occurs when the chamber is cooled and gaseous coolant liquefied by the condenser **19**, the expansion in volume of the gaseous coolant from that near the openings **11** to that of the chamber **17** provides cooling of the gaseous coolant which carries away additional heat from the microchannels **10**.

FIG. **2** shows cross-sectional views of different embodiments of the microchannels **10**. In FIG. **2***a*, microchannels **10** having a rectangular cross-section with openings **11** located below and a source of heat **12** located above, as in FIG. **1**, are shown. Disposed within the microchannels is liquid coolant **21** having meniscuses **23** formed at the openings **11**. Depending upon factors such as the materials used for the substrate **5** and the coolant **21**, the heat flux and the length of the microchannels **10**, the microchannels **10** may have a height **25** to width **26** aspect ratio of five or ten to one. The microchannels are separated by thermally conductive sidewalls **27** that may be of similar dimensions. The meniscuses **23** are rounded outward from the microchannels **10** due to a minimization of potential energies of gravitational and surface tension forces acting upon the liquid coolant **21**.

FIG. **2***b* shows similar microchannels **10**, but inverted in position relative to the heat source **12**, in which case the meniscuses **23** curve inward into the microchannels **10**. FIG. **2***c* shows microchannels **10** that are V-shaped, with openings **11** that are larger in width **26** than the rest of the microchannels, and having a source of heat **12** below. On the other hand, FIG. **2***d* shows microchannels **10** with openings **11** below and a source of heat **12** above, but these microchannels **10** have a tapered cross-section, with the openings **11** having the smallest width **26** of the microchannels **10**. These variations are useful in increasing the cooling due to expansion of the gaseous coolant and may be produced, for example, by crystallographically selective etching of the silicon substrate **5**. It may also be useful to employ microchannels **10** in a non-horizontal position, so that the force of gravity encourages coolant **21** flow along the microchannels **10**.

The surface tension of the liquid coolant **21** is strong enough, given the small dimensions of the microchannels **10**, to provide the force which both draws the liquid coolant **21** into the microchannels **10** and contains it there. The surface tension that confines the liquid coolant **21** in the microchannels **10** also pressurizes it. Within the meniscuses **23**, however, the pressure is diminished, as the meniscuses

are free from surface tension in a direction generally away from liquid coolant **21**. It is well known that the boiling temperature of a fluid varies directly with pressure. Provided that the temperature within the microchannels **10** is fairly uniform, the liquid coolant **21** will vaporize only at the meniscuses **23**, due to the lower pressure and resultant lower boiling point found within the meniscuses **23**. In other words, the boiling point gradient of the liquid coolant **21**, due to the pressure gradient within the microchannels **10**, exceeds the temperature gradient of that coolant **21**, causing the coolant **21** to vaporize only at the meniscuses **23**.

The temperature within the coolant **21** is generally slightly lower further from the heated region, but sidewalls **27** formed of a thermally conductive material such as silicon conduct heat so much better than a coolant such as water that the temperature gradient of the coolant **21** within the microchannels **10** depends primarily on the thermal conductivity of the substrate **5**. The temperature drop between the coolant **21** disposed closest to the heated region and that within the meniscus can be reduced by having either a more thermally conductive substrate **5** or shorter sidewalls **27**.

The chart of the boiling point vs. pressure of water (FIG. 3) shows a steep slope at low pressures and a shallow slope as the pressure approaches atmospheric (1000 Bars). In order to have a large temperature difference between the boiling point of water in the meniscus **23** and that within the microchannel **10** for a given drop in pressure at the meniscus **23**, it is therefore advantageous to operate the device at low pressure. It may also be advantageous to operate the device at low pressure when water is used as the coolant so that phase change cooling takes place at a lower temperature, depending upon the temperature regulation desired.

As a specific example, microchannels **10** separated by vertical silicon sidewalls **27** each having a width of about 10 μm and a height of about 80 μm have been employed with water as the coolant **21**. At an operating pressure of 100 Torr, the water will have a boiling point at the meniscus **23** of about 46° C. Inside a microchannel **10** having a width of 10 μm, the hydrostatic pressure of the surface tension will increase the boiling point to about 65° . Provided that the microchannel sidewalls **27** conduct heat well enough to heat the water in the meniscus to at least 46° C. while the water within the channel does not exceed 65° C., the water will vaporize at the meniscus without boiling within the microchannel **10**.

Since the vaporization of coolant from the meniscus **23** will cause replacement coolant to be drawn into the microchannels **10** via capillary action, the device acts to regulate temperature by beginning to flow and actively cool the heated region once the temperature in the meniscus **23** reaches the boiling point of the coolant disposed there.

Without the aid of a fluid pump, however, the heat flux that can be cooled by the device depends upon the flow of coolant **21** due to capillary action, which is caused by the surface tension of the coolant **21**. The restriction on that flow is due to friction between the walls of the microchannels **10** and the coolant **21** and the viscosity of the coolant **21**. For this reason, it is advantageous for the coolant **21** to have a low viscosity and a high surface tension. It is preferable for the liquid coolant to have a viscosity of less than 0.007 poise, a surface tension of at least 70 erg/cm and a heat of vaporization of at least 200 Btu/lb. Fluids such as water, ammonia, freon, alcohol or any other fluid known in the art may be used. Surface tension is more effective at smaller distances, and thus the flow propelled by capillary action, or capillary pressure, increases as the microchannels **10** are reduced in width. The pressure required to overcome friction between the walls of the microchannel **10** and the coolant **21** and to cause coolant to flow also increases exponentially as the width of the microchannels **10** decreases, and increases linearly with the length of the microchannels **10**.

To put this in perspective it is useful to look at the heat flux produced by a typical apparatus for which the device is to provide cooling. A laser diode bar operating continuously may produce a heat load of 100 watts. The flow rate (without taking into account any additional cooling provided by expansion of gaseous coolant **21** that does not require additional flow of coolant **21**) is simply the heat input divided by the heat of vaporization. Using water again as a convenient example, this implies a flow rate of 0.04 gm/sec to cool the 100 watt load, which may be dispersed over a region 1 mm in length and width.

FIG. **4** is a chart of fluid pressure in Bars vs. channel width in μm, for straight microchannels with a rectangular cross-section containing water. The capillary pressure **30** can be seen to increase dramatically as the width of the microchannels decreases. Also shown is a curve graph **32** of the pressure drop associated with a 0.04 gm/sec flow rate for one mm long microchannels **10** of the same cross-section. Curve **34** represents the pressure drop of 2 mm long microchannels of the same cross-section and flow rate. It can be seen, for example, that the capillary pressure of microchannels **10** of width ten μm easily exceeds the pressure drop due to frictional forces.

For moderate heat loads such as that described above, self-pumped or capillary pumped cooling devices are attractive due to their simplicity. For cooling of larger heat loads that cover larger areas, external pumps may augment the flow induced by capillary action of liquid coolant and convection of gaseous coolant.

Referring now to FIG. **5**, an exploded perspective view of another preferred embodiment of the heat dissipation apparatus of the present invention is shown. A substrate **40**, such as a silicon slice, has passageways **42** and **49** formed therein. Although silicon is used as the substrate in the preferred embodiment, any other well known substrate material would be suitable. Furthermore, although a thermally conductive substrate, silicon, is used in the preferred embodiment, substrate **40** may be formed of a non-thermally conductive material as well.

Passageways **42** and **49** may be formed into substrate **40** using a KOH etch, or any of the numerous etching or carving techniques well known in the art. Although passageways **42** and **49** are rectangularly shaped in the preferred embodiment, alternate shapes are also suitable with the methods of the present invention. Passageway **42**, which functions as an inlet passageway, has a wide opening **44** at one end which passes completely through the bottom of substrate **40**, and a capillary structure **46** at the other end.

Capillary structure **46** at one end of inlet passageway **42**, is formed by carving a plurality of narrow channels into the top surface of substrate **40** which extend into but do not pass completely through substrate **40**, the channels being approximately parallel to and in communication with passageway **42**. The partitions of the substrate material, defining the narrow channels, are separated by distances which are sufficiently narrow such that a liquid may be maintained within region **46** through capillary action. Furthermore, because capillary structure **46** is used to hold liquid coolant through capillary action, and the rest of passageway **42** is used to deliver coolant, the narrow channels forming capillary structure **46** are much narrower than the channels used

to form the rest of inlet passageway **42**. The two ends of inlet passageway **42**, wide opening **44** and capillary structure **46**, are connected to each other through a slender channel **48** which, like the capillary structure **46** of passageway **42** does not pass completely through substrate **40**. Slender channel **48** is formed of a single channel which is much larger than the channels used to form capillary structure **46**.

Passageway **49**, which is used as an outlet passageway, is formed in a manner similar to the way in which inlet passageway **42** was formed. Outlet passageway **49** has a wide opening **50** which is formed by carving an opening completely through substrate **40**. Wide opening **50** is in communication with channel **51** of passageway **49**. Channel **51**, unlike opening **50**, does not pass completely through substrate **40**.

Outlet passageway **49** is formed having a much larger volume than inlet passageway **42**. The larger volume of passageway **49** is necessary to accommodate the flow of vaporized coolant through outlet passageway **49**. Because the coolant in a vaporized state occupies a larger volume than liquid coolant, outlet passageway **49** may be formed having a volume 100 times greater than the volume of inlet passageway **42**.

Additional inlet and outlet passageways **42** and **49** may be formed periodically across the substrate **40** in order to ensure that a plentiful supply of coolant flows to the microchannel array, and to insure that vapor is quickly removed. For example, two inlet passageways may be formed on substrate **40**, and located such that one inlet passageway resides one each side of outlet passageway **49**. Additionally, although opening **44** of inlet passageway **42** and opening **50** of outlet passageway **49** are formed through the bottom of substrate **40**, openings **44** and **50** could be arranged differently if so desired. Additionally the size of openings **44** and **50** may be increased in size in order to allow an increased flow of liquid coolant and vapor, respectively.

A second substrate **52**, which is formed of a thermally conductive substrate such as silicon, has, on its surface, a region **38** heated by a heat producing device, not shown. Although the second substrate is formed of silicon in the preferred embodiment of the present invention, any one of numerous thermally conductive substrates well known in the art would be suitable. The second substrate **52** also has an array of microchannels **10** formed therein. The microchannel array **10** is formed within substrate **52** in a similar manner to which capillary structure **46** of inlet passageway **42** was formed. Channels are carved into the bottom of substrate **52** in the area under the heated region **38**. The channels extend upward into the substrate **52** but do not reach the top surface. The sidewalls of the silicon substrate **52**, which define the narrow channels, are separated by distances which are sufficiently narrow such that a liquid may be disposed within the microchannel array **10** near heated region **38** through capillary action. The channels used to form microchannel array **10** are carved such that they are aligned perpendicular to the channels used to form capillary structure **46** of inlet passageway **42**. In so doing, the liquid coolant will tend to spread along the microchannel array **10** in a direction perpendicular to inlet passageway **42**. Although only a single microchannel array **10** is present in the preferred embodiment of the present invention, a plurality of microchannel arrays **10** may be formed within substrate **52**.

Substrate **52** is then bonded to the top of substrate **40** such that the region of capillary structure **46** of inlet passageway **42**, and the portion of channel **51** of outlet passageway **49**, proximate to capillary structure **46** of inlet passageway **42**, are in fluid communication with microchannel array **10** of substrate **52**. The two substrates **40** and **52** may be fusion bonded, or joined through any other well known silicon processing technique. Further, when the substrates **40** and **52** are both formed of silicon, the flat spot commonly formed into silicon wafers may be used to precisely align the two substrates.

Liquid coolant is supplied and pumped through external means, not shown, to the opening **44** of inlet passageway **42**. The coolant travels through slender channel **48** and is received by capillary structure **46**. Capillary structure **46** holds the coolant through capillary action and, in so doing, acts to regulate the flow of coolant from inlet passageway **42** into microchannel array **10**. The liquid then spreads out along the channels of microchannel array **10** and is retained therein through capillary action. Although a pump is used to supply liquid coolant to inlet passageway **42** in the preferred embodiment of the present invention, other suitable supply means such as capillary action may also be used to supply coolant to inlet passageway **42**. Whether a pump or capillary action is used to supply coolant to microchannel array **10** is dependent upon several factors. These factors may include the type of coolant used, the size of the microchannel array and the channels formed therein, and the amount of heat transferred into microchannel array **10**. If the demand for fresh coolant exceeds the rate at which coolant can be introduced into the microchannel array **10** through capillary action, then a pump may be required.

The liquid coolant which is retained within the channels of microchannel array **10** is surrounded on three sides, such that the liquid coolant is held in close proximity to the heated region **38**. That is, the liquid coolant is in contact with the top and the sidewalls of the channels only. Therefore, the liquid coolant is disposed within the channels such that one surface of the liquid coolant is exposed.

Excess heat generated by a device, not shown, and conductively transferred to heated region **38**, heats and vaporizes the coolant which is held within the capillary structure of microchannel array **10**. As the coolant is vaporized, fresh coolant is supplied to microchannel array **10** through inlet passageway **42** through a pump, not shown. The pressure gradient created by the flow of additional liquid coolant into microchannel array **10** causes the vaporized coolant passed from the exposed side of the liquid coolant to be vented through outlet passageway **49**. In this manner, the flow of fresh liquid coolant into microchannel array **10** through inlet passageway **42** is not impeded by the vaporized coolant produced by the coolant residing in the channels of microchannel array **10**. Likewise, the flow of vaporized coolant through outlet passageway **49** is unimpeded by the flow of liquid coolant into microchannel array **10** through inlet passageway **42**. Furthermore, by venting the vaporized coolant through an outlet passageway **49** which is completely separate from an inlet passageway **42**, the present invention does impede or dry out the path through which the incoming liquid coolant must flow.

In order to facilitate the removal of vapor, outlet passageway **49** may be maintained at a pressure less than inlet passageway **42** through external means. This may provide additional cooling due to expansion of the gaseous coolant **21** according to well known gas laws. The vapor exhausted through outlet passageway **49**, may be vented into the atmosphere, or passed through a condenser where it may be condensed and recirculated to inlet passageway **42**. Although outlet passageway **49** of the preferred embodiment is formed having a wide opening **50** in communication with

a channel **51**, alternate designs are possible. For example, an outlet passageway may be formed having only a single opening which, like opening **50** of outlet passageway **49**, extends completely through substrate **40**. The opening is then located such that when substrates **40** and **52** are bonded together, the opening is located directly under microchannel array **10**. As coolant is vaporized in microchannel array **10**, the vapor passes through the opening in substrate **40** and into a condenser or is vented to the atmosphere.

Thus, as heat is conductively transferred into the liquid coolant and the coolant is heated, vaporization occurs at the exposed surface of the coolant. By passing from the exposed surface of the liquid coolant and out of the channels, the vaporized coolant does not continue to flow along with the liquid coolant through the channels. Thus, the vaporized coolant does not tend to dry out the channels of the microchannel array **10** or cause the temperature of the heated region **38** to rise as found in prior cooling systems.

Additional openings **56** and **58** may also be formed through substrate **52**, when a stacked arrangement of substrates is desired. Opening **56** is arranged such that when substrates **40** and **52** are bonded together, opening **56** will reside directly over opening **44** of inlet passageway **50**. Likewise, opening **58** is arranged such that it will reside directly over opening **50** of outlet passageway **49**.

Referring now to FIG. **6**, as successive substrate layers are stacked vertically, an elastomer gasket **62** having openings corresponding to openings **56** and **58** is placed between each assembly. In so doing, liquid coolant can be supplied to the microchannel array in each layer, and the vapor can be removed from each layer through common corridors **64** and **66** corresponding to openings **56** and **58**, respectively. Microchannels **10** are located proximate to heat sources **12**, which may be laser diode bars. Thus, the cooling apparatus is suitable for either a single layered substrate system as shown in FIG. **5**, or for multi-layered stacked systems as shown in FIG. **6**. Furthermore, both of the above heat removal systems function using only a single external pumping/supply means and a single venting means.

With reference now to FIG. **7**, an alternate embodiment of the present invention is shown in which a bottom substrate layer **70** is attached to a conventional heat sink, not shown. Narrow channels are formed into a large portion of the surface of substrate **70**. The sidewalls **72** of the substrate material define the narrow channels as in the above-described preferred embodiment. The sidewalls **72** in the substrate **70** are separated by distances which are sufficiently narrow such that a liquid may be maintained therebetween through capillary action.

A middle substrate layer **74** has a central opening **76**, and a series of narrow channels carved therethrough. The channels are carved into substrate **74**, such that a capillary structure **78**, as described above, is formed around opening **76** in a direction perpendicular to the alignment of sidewalls **72** in substrate **70**.

A top substrate layer **80**, having a heated region **38** residing on its top surface, is also shown in FIG. **4**. Channels are carved into the bottom of substrate **80** in the area directly under the heated region **38**. The channels extend into the substrate **80** but do not reach the top surface. The sidewalls **27** of the substrate material define the microchannels **10**. The sidewalls **27** are separated by distances which are sufficiently narrow such that a liquid may be maintained therebetween through capillary action. The capillary pressure will tend to keep the liquid coolant in between the sidewalls **27**, and the coolant will spread out along the microchannels **10** in a direction perpendicular to the sidewalls **78** formed in substrate **74**.

A liquid coolant is introduced to the system, and the substrate layers **70**, **74**, and **80**, are bonded together such that the liquid coolant is contained between the layers **70**, **74**, and **80**, and such that the sidewalls of adjacent layers are in fluid communication. The capillary action existing between sidewalls **72**, **78**, and **27** of layers **70**, **74**, and **80**, respectively, will supply liquid coolant into the area under the heated region **38** on top of layer **80**. As excess heat is generated by the device, not shown, and transferred to the heated region, coolant contained between sidewalls **27** will be vaporized. The vaporized coolant will eventually flow from the microchannels **10** of layer **80**, pass through the opening **76** in layer **74**, and contact sidewalls **72** of layer **70**. Since layer **70** is mounted to a heat sink, not shown, the sidewalls **72** will be maintained at a lower temperature than sidewalls **27**. As a result, the vapor will condense onto sidewalls **72** into liquid coolant which can again be supplied through capillary action to microchannels **10** of layer **80** for additional cooling. Thus, a self-contained and fully enclosed system for cooling a heated region is disclosed which requires no external pumping, supplying, or venting means.

Referring now to FIG. **8**, an exploded view of another alternate embodiment of the present invention is shown. In this embodiment, liquid coolant enters housing **90** at input ports **92**. The coolant is pumped through openings **94** in housings **90**. An elastomer gasket **96** having openings corresponding to inlet openings **94** of housing **90** seals plate **98** to housing **90**. Plate **98** has inlet passageways **100** which are on opposite sides of and in fluid communication with narrow grooves **102**. Plate **98** also has exhaust openings **104** located in between narrow grooves **102**. Coolant pumped upwards through inlet openings **94** passes through inlet passageways **100**, and into narrow grooves **102**. Coolant in narrow grooves **102** comes into contact with microchannels **10** formed into layer **106**. The microchannels **10** of layer **106** is formed in the same manner as previous capillary structures described in detail above.

Excess heat generated by devices, not shown, and transferred to heated region **38** at or near the top surface of layer **106** heats and vaporizes the coolant maintained in microchannels **10**. The vapor is then forced by pressure differences from the microchannels **10**, through exhaust openings **104** and elastomer gasket **96** to outlet port **91** of housing **90**.

We claim:

1. A thermal regulation device for cooling a heated region comprising:

a liquid coolant,

a heat conductive body disposed in heat transfer relation relative to said heated region, said body having a wall defining an elongated microchannel within said body proximate to said heated region having an inlet end and an opening extending lengthwise and facing away from said heated region, with said liquid coolant disposed within said microchannel, wall dimensions of said microchannel inducing capillary flow of said liquid coolant and inducing formation of a meniscus by said liquid coolant near said opening, said wall dimensions and meniscus restraining said liquid coolant from boiling but allowing a liquid coolant phase change from a liquid to a gas phase near said opening,

a means for supplying said liquid coolant to said inlet end, and

a means for discharging gaseous coolant formed by said liquid coolant phase change from near said opening,

thereby removing heat from said microchannel.

2. The device of claim 1 wherein said means for discharging gaseous coolant includes a chamber adjoining and in gaseous communication with said opening, said chamber having a gas pressure lower than that near said opening, whereby additional heat is removed from said microchannel due to expansion of said gaseous coolant.

3. The device of claim 1 further defined by means for enhancing liquid coolant flow, thereby removing heat from said microchannel.

4. The device of claim 2 wherein said means for discharging gaseous coolant further includes a condenser in thermal communication with said chamber, said condenser having a temperature inducing condensation of said gaseous coolant at said gas pressure of said chamber.

5. The device of claim 2 wherein said chamber has a gas pressure corresponding to a boiling point temperature in said coolant for which a small increase in said pressure results in a relatively large increase in said boiling point temperature.

6. The device of claim 2 wherein said means for supplying said liquid coolant to said inlet end includes a capillary having one end in fluid communication with said inlet end and another end disposed in said chamber adjacent to said condenser, whereby condensed coolant is drawn by said capillary to feed said microchannel.

7. The device of claim 1 wherein said microchannel is further defined by an end wall and a pair of sidewalls, said end wall proximate to said heated region and covered with liquid coolant, said sidewalls contiguous with said end wall and said opening.

8. The device of claim 7 wherein said sidewalls are substantially parallel with each other.

9. The device of claim 7 wherein said sidewalls are closer together near said end wall than near said opening.

10. The device of claim 7 wherein said sidewalls are closer together near said opening than near said end wall.

11. The device of claim 1 having a plurality of inlet ends separated by said opening.

12. The device of claim 2 wherein said means for supplying said liquid coolant to said inlet end includes a fluid pump having an outlet in fluid communication with said inlet end of said microchannel.

13. The device of claim 1 wherein said liquid coolant has a low viscosity, a high surface tension and a high heat of vaporization.

14. The device of claim 2 wherein said means for discharging gaseous coolant further includes a gas pump in gas flow communication with said chamber.

15. The device of claim 4 wherein said means for supplying said liquid coolant to said inlet end includes a conduit having one end in fluid communication with said inlet end and another end disposed in said chamber adjacent to said condenser and at a higher gravitational potential than said inlet end, whereby condensed coolant flows down said conduit to feed said microchannel.

16. A device for cooling a heated region comprising:

a liquid coolant,

a heat conductive substrate disposed in heat exchange communication with said heated region, said substrate having walls defining a plurality of mostly parallel elongated microchannels proximate to said heated region having inlet ends and outlet openings extending longitudinally and facing away from said heated region with said liquid coolant disposed within said microchannels, wall dimensions of said microchannels inducing capillary action in said liquid coolant and inducing formation of meniscuses by said liquid coolant near said openings, said wall dimensions restraining said liquid coolant from boiling but allowing a liquid coolant phase change from a liquid to a gas phase near said meniscuses,

a means for supplying said liquid coolant to said inlet ends, and

a means for discharging said gaseous coolant from near said outlet openings, thereby removing heat from said microchannels.

17. The device of claim 16 wherein said means for discharging gaseous coolant includes a chamber adjoining and in gaseous communication with said outlet openings, said chamber having a gas pressure lower than that near said outlet openings, whereby additional heat is removed from said microchannels due to expansion of said gaseous coolant.

18. The device of claim 17 further comprising a second substrate bonded to said thermally conductive substrate, said second substrate having an inlet passageway with a first and second end formed therein, and an outlet passageway with a first and second end formed therein, said first end of said outlet passageway including said chamber.

19. The device of claim 18 wherein said means for supplying said liquid coolant to said inlet ends includes a plurality of capillaries disposed in said first end of said inlet passageway in fluid communication with said inlet ends.

20. The device of claim 19 wherein said means for discharging said gaseous coolant from said outlet openings includes a condenser adjoining said second substrate in thermal communication with said outlet passageway, said condenser having a temperature inducing condensation of said gaseous coolant at said gas pressure of said chamber.

21. The device of claim 20 wherein said means for supplying said liquid coolant to said inlet end includes said second end of said outlet passageway being disposed adjacent to and in fluid communication with said second end of said inlet passageway.

22. The device of claim 18 wherein said second substrate has an inlet bore extending therethrough and in fluid communication with said inlet passageway, and an outlet bore extending therethrough and in gaseous communication with said outlet passageway, such that liquid coolant may be introduced into said inlet passageway and gaseous coolant may be removed from said outlet passageway from outside said substrate.

23. The device of claim 22 disposed adjacent to a plurality of identical devices wherein corresponding inlet bores are in fluid communication with each other and corresponding outlet bores are in gaseous communication with each other.

24. The devices of claim 23, wherein said means for supplying liquid coolant to said inlet end further comprises a source of liquid coolant disposed outside said devices and in communication with said inlet bores.

25. The devices of claim 24 wherein said means for discharging gaseous coolant from said outlet openings further comprises a repository of gaseous coolant disposed outside said devices and in gaseous communication with said outlet bores.

26. The devices of claim 25 wherein the means for supplying said liquid coolant to said inlet end includes a fluid pump in communication with said source of liquid coolant.

27. The devices of claim 26 wherein the means for discharging said gaseous coolant from said outlet openings includes a gas pump in gaseous communication with said repository of gaseous coolant.

28. The devices of claim 27 wherein said means for

supplying said liquid coolant to said inlet ends and said means for discharging said gaseous coolant from said outlet openings includes a condenser in thermal communication with said gaseous repository and having a temperature inducing condensation of said gaseous coolant disposed within said gaseous repository, said gaseous repository being in fluid communication with said source of liquid coolant.

29. The device of claim **17** wherein said liquid coolant has a low viscosity, a high surface tension and a high heat of vaporization.

30. A device for cooling an electronic apparatus comprising:

a liquid coolant,

a thermally conductive body having a surface in heat exchange communication with said electronic apparatus and having a plurality of thin walls protruding in a direction generally away from said surface, said walls defining at least one elongated microchannel having an inlet and having an opening extending lengthwise facing away from said surface, said wall dimensions of said microchannel inducing capillary action in said coolant and inducing formation of a meniscus by the coolant near the opening, said liquid coolant vaporizing at said meniscus due to heat from said body, but constrained from boiling by said meniscus and said walls,

a pressure means for supplying said liquid coolant to said inlet, and

a venting means for removing gaseous coolant from said opening.

31. The device of claim **30** wherein said venting means includes a chamber adjoining and in gaseous communication with said opening, said chamber having a gas pressure lower than that adjacent to said meniscus, whereby additional

cooling occurs due to expansion of said gas.

32. The device of claim **31** further comprising a condenser in gas flow communication with said chamber, said condenser having a temperature inducing condensation of said gaseous coolant at said gas pressure of said chamber.

33. The device of claim **32** wherein said pressure means includes a capillary having one end in fluid communication with said inlet and another end in fluid communication with coolant condensed by said condenser, whereby condensed coolant is drawn by said capillary to feed said microchannel.

34. A thermal regulation device for cooling a heated region comprising:

a liquid coolant,

a heat conductive body disposed in heat transfer relation relative to said heated region, said body having a wall defining an elongated microchannel within said body proximate to said heated region having a pair of inlet ends and an opening extending lengthwise therebetween distal to said heated region, with said liquid coolant disposed within said microchannel, wall dimensions of said microchannel inducing capillary flow of said liquid coolant and inducing formation of a meniscus by said liquid coolant near said opening, said wall dimensions and meniscus restraining said liquid coolant from boiling but allowing a liquid coolant phase change from a liquid to a gas phase near said opening,

a means for supplying said liquid coolant to said pair of inlet ends, and

a means for discharging gaseous coolant formed by said liquid coolant phase change from near said opening, thereby removing heat from said microchannel.

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